Studying Interfacial Specific Resistance of Fe(001)/Ag (001) Interface and Effective Way to Enhance the MR Output in a CPP-GMR Device

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学位論文題目	Studying interfacial specific resistance of Fe(001)/Ag(001) interface and effective way to enhance the MR output in CPP-GMR device (Fe/Ag (001)界面抵抗の研究と CPP-GMR デバイスの MR 出力の効果的増大法に関する研究)
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論文内容要約

In this dissertation, I report on the studying interfacial specific resistance of (001)-orientated Fe/Ag interface and effective way to improve the CPP-GMR output (total resistance-change product area, ΔRA) even composed of only 3*d*-magnetic-element layer and Ag spacer layer. As magnetic layers were used the artificially ordered B2 state of $Fe_{50}Co_{50}$ alloy, which has particular interest for expected that creating a high spin polarized current. The B2-ordered $Fe_{50}Co_{50}$ film was successfully fabricated by artificially alternating the deposition of two different monatomic of Fe and Co layers (**A**lternate **M**onatomic **L**ayer [Fe/Co]). The fabrication process of the artificially ordered B2 state of $Fe_{50}Co_{50}$ layer was established (Ch. 3). Pseudo spin-valves (PSVs) with a stacked consisting of artificially B2 state FeCo alloy layers (t_F:3~5 nm thick) and Ag spacer layer (t_N:5 nm thick) with and without very thin Fe insertion layer (t_{Fe}:1 nm thick) between ferromagnetic (F) and nonmagnetic (N) layers in stacked GMR active layer. Our CPP-GMR device with the thin Fe insertion layer, we can achieved that enhanced ΔRA (t_F = 5 nm) up to 4.2 m$\Omega\mu m^2$ compared with that of the CPP-GMR device without thin Fe insertion layer (Ch.4). In order to understand the origin that the improvement of ΔRA within two types of PSVs, we deduced the bulk spin scattering asymmetry β, and interfacial spin scattering asymmetry γ, and spin dependent interfacial specific resistance $AR^*_{F/N}$, which are a crucial values for improving the CPP-GMR output, by using the modified Valet-Fert theory (Ch.5). Our finding in Ch.5 indicate that $AR^*_{F/N}$ contribute more to the large CPP-GMR output. In order to clarify this point, we have a further investigation of the variation of the interfacial parameters as a function of the Fe concentration *x* in a Fe_xCo_{100-x}/Ag interfaces (Ch.6). To demonstrate the effectiveness of this method which further contributes to a high MR output for these devices, we fabricated PSVs consisting of two artificial ordered $Fe_{50}Co_{50}$ alloy as F layers and Ag spacer layer with a four Fe (001)/Ag interface (Ch.7). Finally, summarized and further directions of the potential of the CPP-GMR devices with conventional 3*d*-magnetic element layer (Ch.8). In total, 8 chapters are presented.

Chapter 1. Introduction

Current-perpendicular-to-plane giant magnetoresistive (CPP-GMR) devices have been studied extensively for their potential applications in readers of ultrahigh density hard disk drives (HDDs). However, the biggest drawback for applications, the performance of the signal-to-noise(S/N) ratio is degraded by low MR ratio for CPP-GMR devices. In order to improve the CPP-GMR output, signified the understanding of contribution of spin dependent electron scattering to the total resistance change in metallic CPP-GMR devices. Thus, materials choice under understanding the mechanism of two types of spin dependent scatterings (i. e. β, γ and $AR^*_{F/N}$) are indispensable for the enhancement of CPP-GMR output. For many years, two kinds of spin asymmetries (β, γ) were believed to be the most important determinant for improvement of CPP-GMR output. We suggest that interfacial spin dependent scattering with enhanced interfacial specific resistance are more dominantly contributes to a high CPP-GMR- output. Stiles and Penn have reported theoretical results showing quite different transmission probabilities of spin-up and spin-down electrons on the Fermi surface at the Fe (001)/Ag interface [M. D. Stiles and D. R. Penn, Phys. Rev. B **61**, 3200 (2000)]. Therefore at this interface, an almost complete transmission from the majority spin state of Fe into the Ag is predicted due to well matched their band structure; in contrast, a strong reflection for the minority spin occurs, related to the mismatching of the minority electron band structure. We considered that the spin-dependent interface resistance at the F/N interface is a potential key factor in improving the MR output, even for CPP-GMR devices that use conventional 3*d* transition materials as the F layer; these materials have a relatively simple crystal structure and are commonly used for many industrial applications. In this study, we investigated the effect of the Fe (001)/Ag interface on the MR output in a new type of hybrid device, which is a spin filter CPP-GMR based on an artificial B2 state $Fe_{50}Co_{50}$ alloy.

Chapter 2. Experimental procedure

This chapter described how can fabricate the B2-ordered $Fe_{50}Co_{50}$ alloy and Ag spacer layer and our PSVs sample were micro-fabricated into CPP pillar geometry, using a combination of electron-beam(or photo) lithography and Ar ion etching. Then, resistance was measured by dc four-probe method with a measuring current of 1 mA under applied magnetic field.

Chapter 3. Artificially ordered B2 state of $Fe_{50}Co_{50}$ alloy

The B2-ordered state of $Fe_{50}Co_{50}$ alloy used in the work. This is mainly because it has several useful characteristics, such as structural stability, high Curie temperature and a simple structure. However, disordered $Fe_{50}Co_{50}$ alloy normally shows a body centered cubic(bcc) in which the Fe and Co elements are distributed randomly. Generally, the ordering reaction between Fe and Co occurs at high substrate temperatures over 730°C. We have succeeded in fabricating an artificially ordered B2 state in the FeCo alloy using an alternate monatomic deposition method, in which monolayers (1.4 Å)of Fe and Co were deposited alternately with suitable deposition rate at substrate temperature of 75 °C using the electron-beam evaporator. Using the neutron diffraction measurement, we found that an ordering parameter S ~ 0.7 indicates a highly ordered $Fe_{50}Co_{50}$ structure, suggesting that each of the Fe and Co monolayers have clearly distinct. The resistivity of the B2-ordered state of $Fe_{50}Co_{50}$ alloy found to be 14.2 μΩcm which is lower than those of Fe_xCo_{100-x} alloy because, the binary alloys of atoms are positioned ordered fashion in the crystal structure landing to the low resistivity from the reduced electrons scattering.

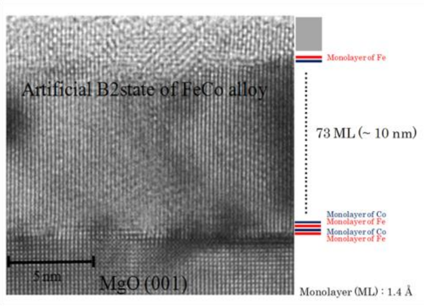

Fig.1 TEM image of artificial B2 state of FeCo alloy

Chapter 4. CPP-GMR devices with B2 state of FeCo alloy and Ag spacer

We prepared the PSVs consisting of the ordered FeCo alloy and Ag layer. we found an MR ratio of more than 19 %, corresponding to a ΔRA of up to 3.1 mΩ μm^2 and an RA less than 15 mΩμm^2 for t_F= 5 nm. However, obtained ΔRA value was rather lower than for the prediction value because it also contained one monolayer of the Fe (001)/Ag interface in the GMR active layer. One of possible reason for this result may be that a Co/Ag interface was formed by mixing when a spacer layer is deposited on the bottom F layer using the sputtering method with a high deposition energy. We also prepared PSVs consisting of the ordered FeCo alloy and an Ag layer with an inserted thin Fe layer at the F/N interface to suppress the degradation of the Fe(001)/Ag interface effect resulting from the formation of a Co/Ag interface. For t_F = 5 nm with a thin (1 nm) Fe layer, we found an MR ratio of more than 24%, corresponding to a ΔRA of up to 4.2 mΩ μm^2 and an RA less than 17 mΩμm^2. The ΔRA should increase linearly with increasing F layer thickness within its spin diffusion length. However, improvement of around 1 mΩμm^2 compared with that of CPP-GMR device without insertion layer cannot be explained only by the bulk spin dependent scattering contribution in the F layers. Consequently, the enhancement of the ΔRA is likely due to the enhancement of interfacial scattering at the Fe (001)/Ag interface from the inserted thin Fe layer between the F and N layers.

Chapter 5. Analysis of spin asymmetries of CPP-GMR

In this chapter, we evaluated the bulk spin asymmetric scattering coefficient β, the interface spin asymmetric scattering coefficient γ, and the interface specific resistance $AR^*_{F/N}$ by analyzing the ΔRA dependence on the F layer thickness using the modified Valet-Fert model. A quite large β value of 0.82 was derived from the Valet-Fert fitting, in good agreement with our previous result of 0.81 indicating good reproducibility.[T. Mano and M. Sahashi *et al*., IEEE Trans. Magn. **45**. 3460 (2009)] It is interesting to note that these fitting results suggest that the interfacial specific resistance $AR^*_{F/N}$ contributes to a large MR output primarily as a result of the improved ΔRA, which is thought to be 1 mΩμm^2, due to the Fe insertions. It is worth noting also that from the value of $AR^*_{F/N}$ for the Fe(001)/Ag interface, the interfacial specific resistances for the up and down channels were evaluated to be $AR_{F/N}\uparrow$ ~1.08 mΩμm^2 and $AR_{F/N}\downarrow$ ~ 7.98 mΩμm^2.

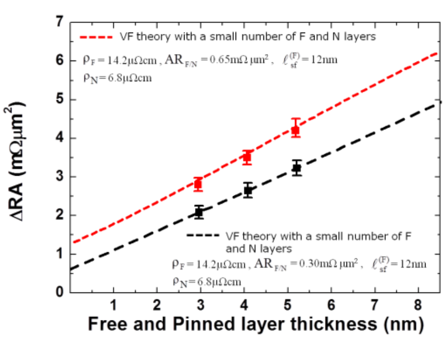

Fig.2 The variation of ΔRA for the tF thickness dependence and dashed line represents the fitted lines by the modified VF model

Chapter 6. Investigating the variation of interfacial parameters at Fe_xCo_{100-x}/Ag interfaces

Our findings in Ch.5 indicate that $AR^*_{F/N}$ contribute more to the large CPP-GMR output. In order to clarify this point, we have a further investigation of the variation of the interfacial parameters as a function of the Fe concentration x in a Fe_xCo_{100-x}/Ag interfaces. We have extracted the interfacial parameters. As a results, we found that there are no remarkable different the interfacial spin different asymmetry, γ for Fe concentration dependence in Fe_xCo_{100-x}/Ag interfaces. However, interfacial specific resistance was dramatically increase lending to large spin dependent interfacial specific resistance by changing to more Fe-rich/Ag interface. The interfacial specific resistance at (001)-orientated Fe/Ag epitaxial interface experimentally to be $AR_{F/N}$~ 0.65 mΩμm^2 by measuring RA in the parallel magnetization states of Fe/Ag multilayers. This indicates good band matching for the Fe majority electron band structures to that of Ag, whereas the Fermi surface of Fe is very different to that of Ag for the minority states, leading to a strong reflection for these spins.[M. D stiles, J. Appl. Phys. **79**, 5805 (1996)]

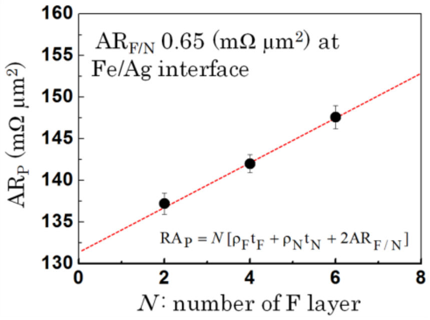

Fig. 3 Interfacial specific resistance at Fe/Ag interface

Chapter 7. CPP-GMR device with four (001)-orientated Fe/Ag interface

To demonstrate the effectiveness of this method which further contributes to a high MR output for these devices, we fabricated PSVs consisting of $Fe_{50}Co_{50}$ alloy/Ag/$Fe_{50}Co_{50}$ alloy with a four Fe (001)/Ag interface, where each layer had a thickness of 5 nm; we obtained an MR ratio above 20% with a large ΔRA of up to 6.2 mΩ μm^2 and an RA of less than 32 mΩμm^2. it is well known from other previous studies that CPP-GMR devices based on 3*d* conventional materials showed an extremely low MR performance of a few percent, corresponding to a ΔRA less than 1.5 mΩμm^2 and a MR ratio as small as a few[H. Yuasa and M. Sahashi *et al.*, J. Appl. Phys. **92**, 2646 (2002)]. In conclusion, we succeeding in achieving a large interfacial specific resistance of 2.17 mΩμm2, leading to a large resistance-change area product of 6.2 mΩμm2, i.e., a high MR output of more than 20% (potentially ~40%).Thus, our demonstration of a high GMR effect shows clearly why we have focused on the interfacial spin asymmetry and the interfacial specific resistance for improving the MR output. This is primarily due to the fact that improvement of $AR^*_{F/N}$ is strongly suggested to play a key role in achieving a high GMR.

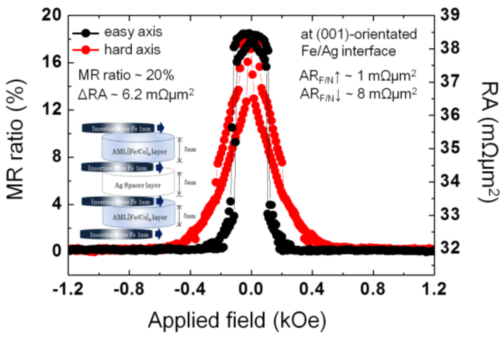

Fig.4 MR curve for CPP-GMR with four insertion layers

Chapter 8. Summary

In this chapter, final conclusions are outlined, and further directions are summarized.

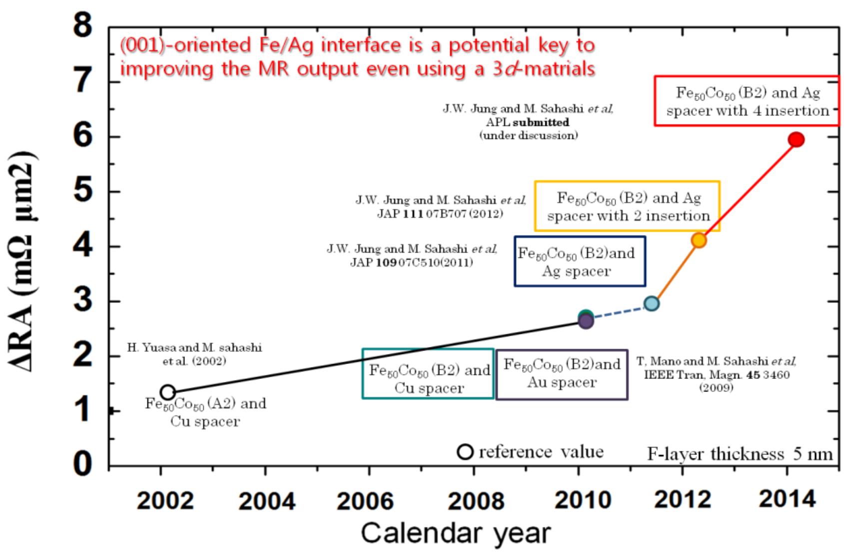

Fig.5 Development of CPP-GMR output which consisting 3*d*-conventional materials of at room temperature.